Sea surface slope statistics from a low-altitude aircraft

D. Vandemark[1], *T. Crawford*[2], *R. Dobosy*[3], *T. Elfouhaily*[4] *and B. Chapron*[5]

[1] NASA/GSFC Code 972,
Wallops Flight Facility, Wallops Island, VA 23337
(757) 824-2038, FAX -1036; email vandemark@gsfc.nasa.gov
[2]NOAA/ARL/FRD, Idaho Falls, ID USA
[3]NOAA/ARL/ATDD, Oakridge, TN USA
[4] JHU/APL, Laurel, MD, USA
[5] IFREMER/Centre de Brest, Plouzané, FRANCE

A new combination of sensors for concurrent aircraft measurement of surface waves and turbulent fluxes has been developed. A simple three laser altimeter arrangement is used to directly measure the 2-D slope of intermediate scale waves and the surface wave profile. A CW scatterometer at Ka-band is used to infer changes in the shorter-scale (less than 1 m) slope variance. This NOAA Long-EZ aircraft then provides high resolution air-sea data with application to such topic as the modulation transfer function, large-scale atmospheric impacts on the sea surface, and characterization of sea surface statistics.

I. INTRODUCTION

Ocean surface remote sensing techniques often rely on scattering or emission linked to shorter-scale gravity-capillary ocean wavelets. However, it is increasingly apparent that slightly longer wavelengths of O(10 to 500 cm) are vital components in the robust sea surface description needed to link varied global remote sensing data sets. The field of microwave remote sensing has a specific need for improved surface slope definition for varied applications such as ocean radiometry, altimetry and forth-coming GPS backscatter experiments. This paper describes a laser and radar sensor suite developed to measure sea surface slope variations in the field using an aircraft flying at altitudes from 10-20 meters. We provide sample measurements with application to *pdf* determination, air-sea coupling in the coastal zone, and study of the satellite altimeter electromagnetic (EM) bias correction.

II. AIRCRAFT MEASUREMENTS

The NOAA Long-EZ research aircraft has been equipped to collect simultaneous atmospheric and sea surface roughness measurements. Turbulent fluxes are computed using fast rate sensors that are primarily located in 9-port pressure sphere mounted on the nose boom [1]. These data are complemented by a combination of laser altimeters and radar scatterometer mounted near the aircraft's center of gravity. The surface measurement geometry shown in Figure 1 Two-dimensional surface slope is measured using simultaneous range measurements from three compact short-range laser altimeters (Riegl model #LD90-3) mounted in an equilateral triangle arrangement with spacing of 0.9 m. In addition, all three lasers provide independent wave elevation profiles after GPS-aided correction for aircraft altitude. Laser range precision is 1 cm rms while vertical motion correction is 20 cm rms. The measurements are made along-track at approximately 1 m intervals setting the spatial scale of these measurements to cover waves of intermediate to long scale. Products available for this array then include surface elevation, the two-dimensional slope distribution, and the cross- and along-track 1-D slope distributions.

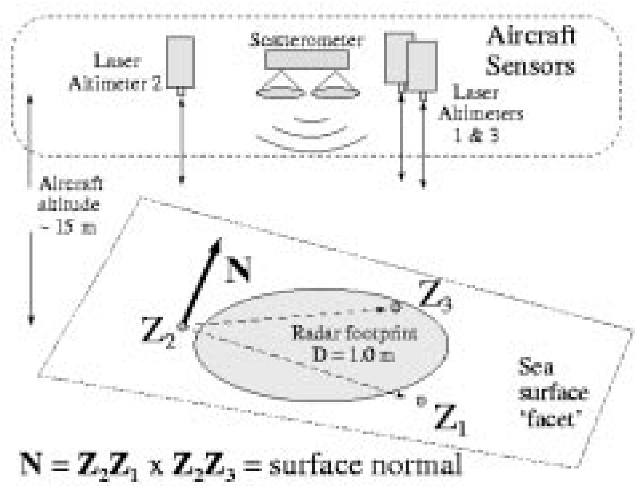

Fig. 1. This sketch shows the configuration of three lasers and a Ka-band scatterometer all nadir looking. The distance between the laser is about 1m. The scatterometer is in the middle of the lasers and produces a footprint of about 1m.

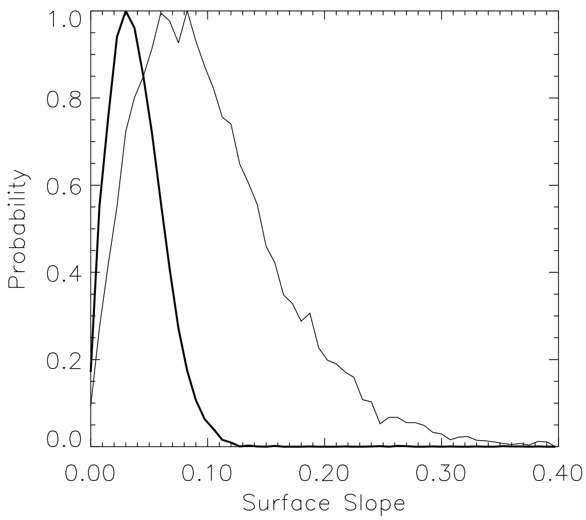

Fig. 2. Omnidirectional slope *PDF* inferred from two-dimensional slope measurements. Small slopes over the inland water (thick solid) and higher slopes on open ocean (thin solid)

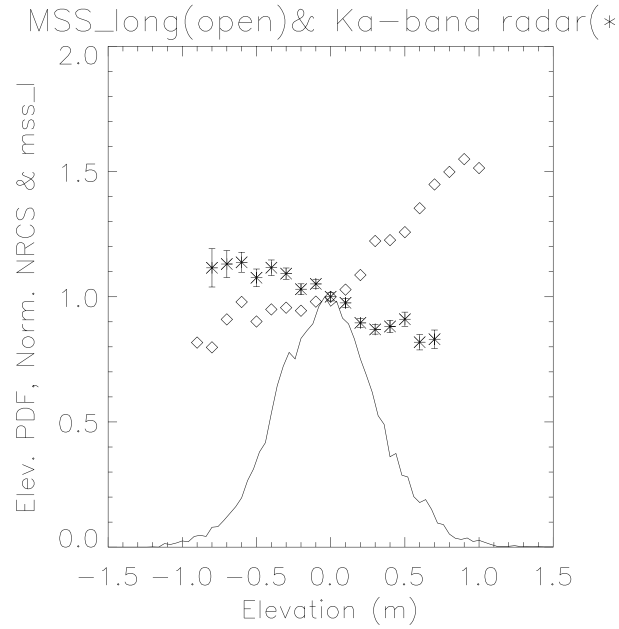

Fig. 3. Average of radar backscatter (stars) and intermediate scale slope variance (diamonds) versus sea surface elevation. Variation with elevation demonstrates the electromagnetic bias.

To augment the lasers, a down-looking mm-wave radar scatterometer is centered within the laser array to measure radar backscatter simultaneously with the laser slope. The 36 GHz radar's footprint is nominally 1 m in diameter (Fig. 1). This backscatter measurement can be considered as a high spatial resolution version of the satellite altimeter. Near-vertical radar backscatter is inversely proportional to the small-scale surface slope variance and to the tilt of the underlying (laser-measured) surface facet. Together the laser and radar data provide information on wave roughness from the longest scales down to about 1 cm.

There have been several recent deployments of this aircraft off the coast of North Carolina for both coastal and open-ocean applications. These include participation in the Office of Naval Research's Shaoling Waves Research Program, and NASA's JASON-1 altimeter research program. The following examples come from data collected over the western Atlantic ocean in Nov. of 1997 and 1998.

III. SAMPLE RESULTS

The three lasers provide a reliable slope measurement of waves longer than a meter for the present setup. Figure 2 shows the sensitivity of the slope *PDF*s to the state of the surface. *PDF*s from the inland water, where long waves are almost absent, look very different from those obtained for open ocean conditions. It should be noted that not only the mode of the histograms is occurring at lower slopes for the inland waters but also the tail is much shorter than the one from the open ocean.

Since surface elevation is measured concurrently with surface slopes, expected correlations can be studied between elevation and slope. These measurable correlations are an indication of the nonlinear nature of water waves. This nonlinearity is also reflected in the radar backscatter data. Such correlation between elevation and slopes induces an important electromagnetic bias which induces a significant error on the range estimation by radar altimeters. Figure 3 shows how both long-wave slopes and nadir radar backscatter are correlated with surface elevation. Hydrodynamic modulations of short waves by longer ones could account for most of the correlation. The slope variance is also a measure of roughness and therefore from Figure 3 one could say that, on average, waves are rougher (high variance) near their crests (high elevation). However, the averaged backscatter returns are higher when the surface is smoother for a nadir looking radar. This reverse behavior of the correlation between radar backscatter and surface elevation causes the electromagnetic bias to be negative. For our case study the electromagnetic bias is on the order of -2% of the significant wave height.

Finally, we present scatter plots of the radar-inferred and laser-measured slope variances versus measured wind speed. The lines on the plots are clean (upper) and slick (lower) models for slope behavior versus wind speed [2]. One can see that, as expected, the Ka-band radar infers values close to the clean surface optically-derived data [2]. The slick surface model was developed for intermediate scale slopes by damping all waves shorter than about 30 cm. As one can see in the bottom panel, our longer-wave laser measurements fall just under that model. There is clear wind dependence in both measured parameters and also significant scatter. Large deviations, especially in the long-scale data, are due to data collection under non-equilibrium wind wave conditions such as right near the coast or over the inland waterway.

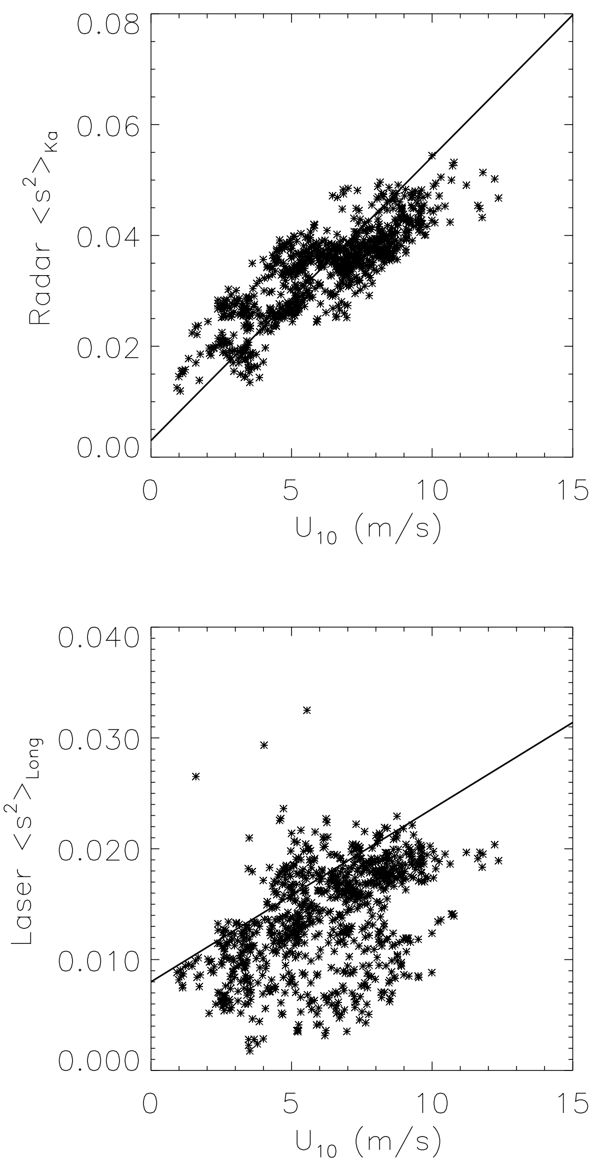

Fig. 4. Top panel compares the slope variance as seem by the nadir looking radar function of wind speed. The solid line is a model based on optical data by Cox and Munk [2] for a clean surface. Bottom panel shows how long wave slopes as estimated by the three lasers is lower than the slick measurements of Cox and Munk.

IV. ACKNOWLEDGMENTS

Our thanks to E. Dumas and D. Hines. This work is supported by the Office of Naval Research and NASA's Earth Science Enterprise.

V. REFERENCES

[1] T.L. Crawford, R.T. McMillen, R.J. Dobosy, and I. MacPherson, "Correcting airborne flux measurements for aircraft speed variation," *Bound. Layer Met.*, vol. 66, pp. 237–245, 1993.

[2] C.S. Cox and W.H. Munk, "Statistics of the sea surface derived from sun glitter," *J. Mar. Res.*, vol. 13, pp. 198–227, 1954.